REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
Sep 2009

2. REPORT TYPE

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Non-Equilibrium Gas Dynamics - From Physical Models to Hypersonic Flights
(Dynamique des gaz non-équilibrés – Des modèles physiques
jusqu'au vol hypersonique)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research and Technology Organisation (NATO)
BP 25, F-92201 Neuilly-sur-Seine Cedex, France

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
RTO-EN-AVT-162

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A: Approved for public release

13. SUPPLEMENTARY NOTES
Supporting documents are attached to the report as separate files (MS Word, PDF, HTM). Papers presented during the AVT-16

14. ABSTRACT
In-depth knowledge of gas dynamics at hypersonic speeds is required to define the environment and requirements for the design and safe operation of space vehicles, planetary probes, and rockets. Development of physical models and numerical methods has enabled major advancements in our approach to the design of vehicles, and has minimized the needs for extensive flight tests. However, there remain many challenges in our ability to model the hypersonic regime. Transport of mass, momentum, and energy in hypersonic flows in thermo-chemical non-equilibrium requires further development of the physical models and reliable experimental data to guide and validate these models. The complexity of the physics in the hypersonic regime presents unique challenges for measurement techniques and flight tests.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	SAR	7	19b. TELEPHONE NUMBER *(include area code)*
u	u	u			

NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

AC/323(AVT-162)TP/279

www.rto.nato.int

RTO EDUCATIONAL NOTES **EN-AVT-162**

Non-Equilibrium Gas Dynamics - From Physical Models to Hypersonic Flights

(Dynamique des gaz non-équilibrés – Des modèles physiques jusqu'au vol hypersonique)

Papers presented during the AVT-162 RTO AVT/VKI Lecture Series held at the von Karman Institute, Rhode St. Genèse, Belgium.

Published September 2009

The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

The content of this publication has been reproduced directly from material supplied by RTO or the authors.

Published September 2009

ISBN 978-92-837-0091-3

Non-Equilibrium Gas Dynamics
From Physical Models to Hypersonic Flights

(RTO-EN-AVT-162)

Executive Summary

Development of hypersonic flights for aerospace transport industry, space agencies, and defense programs requires in-depth knowledge of non-equilibrium gas dynamics effects for accurate design and safe operation of spacecraft, planetary probes, and rockets. The transport of mass, momentum, and energy in flows in thermo-chemical non-equilibrium involves kinetic processes at a microscopic level and relies on the set-up of fine experimental apparatus and development of physical models built and elaborated along with the demand of aerospace activities.

Objectives of this special course are to review the up-to-date theoretical models describing non-equilibrium effects, the experimental techniques, as well as the numerical simulation strategies specific to aerothermochemistry, in particular, aiming at better predicting the thermal loads on atmospheric entry bodies.

The course is organised to expose thermo-chemical non-equilibrium models for gas dynamics and databases for kinetic mechanism and radiation phenomenon. Theoretical basis are given and microscopic mechanisms are discussed in details, it allows to have a wide view on the collection of phenomena to integrate for an efficient energy transfer modelling. Advanced modelling are also proposed including kinetics and radiation in simple application cases. Experimental techniques for the validation of the theoretical models are presented in a following section devoted to high enthalpy facilities operation for simulating planetary re-entry conditions and the optical measurements associated for the diagnostic of these non-equilibrium flows. The course is concluded by a very comprehensive presentation of numerical capabilities applied to atmospheric entries. The interaction with the physical modelling is focus in particular as the potentialities and the limits are underlined for the current aerospace applications.

In overall the lectures give a complete perspective from the basic research to the applied studies in the context of hypersonic flights.

Dynamique des gaz non-équilibrés
Des modèles physiques jusqu'au vol hypersonique

(RTO-EN-AVT-162)

Synthèse

Le développement des vols hypersoniques au profit de l'industrie du transport aérospatial, des agences spatiales et des programmes de défense exige une connaissance détaillée des effets de la dynamique de gaz non équilibrés pour la conception précise et l'exploitation sûre des vaisseaux spatiaux, des sondes planétaires et des fusées. Les transferts de masses, leur moment, et l'énergie dans les flux en non équilibre thermo-chimique impliquent des processus cinétiques à un niveau microscopique et reposent sur l'installation d'un appareillage expérimental fin et sur le développement de modèles physiques construits et élaborés en accompagnement des activités aérospatiales.

Les objectifs de cette session spéciale sont de passer en revue les derniers modèles théoriques en vigueur décrivant les effets du non-équilibre, les techniques expérimentales, aussi bien que les stratégies de simulation numérique spécifiques à la chimie aéro-thermique. Elle vise, en particulier, à mieux prévoir les charges thermiques qui s'appliquent sur les corps en rentrée atmosphérique.

La session est organisée de façon à présenter les modèles thermo-chimiques de non-équilibre pour la dynamique des gaz et les bases de données pour les mécanismes cinétiques et les phénomènes de rayonnement. Les bases théoriques en sont données, et les mécanismes microscopiques sont discutés dans le détail. Cela permet d'avoir une large vue sur l'accumulation des phénomènes à intégrer pour obtenir une modélisation efficace du transfert d'énergie. Il est également proposé une modélisation avancée incluant la cinétique et le rayonnement dans des cas simples d'application. Des techniques expérimentales de validation des modèles théoriques sont présentées dans une section suivante dédiée à l'utilisation de laboratoires pour les hautes enthalpies en vue de simuler des conditions de rentrée planétaire et de donner les mesures optiques associées nécessaires au diagnostic de ces écoulements en non-équilibre. La session s'est terminée par une présentation très compréhensible des possibilités numériques appliquées aux rentrées atmosphériques. L'accent fut mis sur l'interaction avec la modélisation physique en particulier car les potentialités et les limites furent soulignées pour ce qui concerne les applications aérospatiales courantes.

Dans leur ensemble les conférences donnent une perspective complète allant de la recherche fondamentale aux études appliquées dans le contexte des vols hypersoniques.

AVT-162 Programme Committee

Lecture Series Directors

Dr. Olivier Chazot
von Karman Institute
Chaussée de Waterloo 72
1640 Rhode-Saint-Genèse
Belgium

email: chazot@vki.ac.be

Dr. Thierry Magin
Stanford University
Center for Turbulence Research
488 Escondido Mall
Stanford, CA 94305-3035
United States

email: magin@stanford.edu

Panel Executive

Dr. Dennis Göge
RTA
Tel: +33 (0) 1 55 61 22 85
FAX: + 33 (0) 1 55 61 96 41

E-mail: goeged@rta.nato.int